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High-resolution holographic image projection at visible and ultraviolet wavelengths

I. N. Ross, G. M. Davis, and D. Klemitz

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Holograms of resolution test masks have been recorded in photoresist using visible and ultraviolet lasers. Reconstructed images have been projected onto and recorded in photoresist by lithography. Speckle-free submicron resolution has been achieved using simple and inexpensive optical systems and using lasers with limited coherence. Using these techniques with excimer lasers single-shot recording with exposure time of ~20 ns and multishot reconstruction with exposure time ≤ 1 s are possible for image fields up to 10 cm in diameter.

I. Introduction

The manufacture of microcircuits demands an ever increasing throughput on very large scale integration (VLSI) machines and an ever decreasing size of the smallest resolvable element. The advent of the rare-gas halide lasers operating in the ultraviolet has offered possible improvements in both these areas and considerable effort has already been injected into using these lasers coupled to existing contact, proximity, and imaging printers.¹ However improvements so achieved will be restricted because current throughputs are as much limited by the need to step and repeat on many current machines as by the actual exposure time, while the resolution is as much limited by design and manufacturing quality of the imaging system as by the wavelength itself.

Both these limitations can be removed by using a holographic process since the optics can be far from diffraction-limited so making it possible to remove the limitation on field size (which limitation necessitates the step-and-repeat action of current machines). Holography has potentially a number of other advantages. The correct image referencing is simpler since it is referenced into the same position as the original object (mask in the microcircuit application) and the original object position is not critical. Point defects or scratches accruing on the hologram are not important

if the hologram is recorded in an out-of-focus plane of the object. The geometry is very flexible and can generally be adjusted to suit requirements or convenience. The numerical aperture of the holographic imaging system can easily be made very large giving a potential resolution equal to the wavelength (0.19 μm for the ArF laser).

Holography, both in the usual lapsed time sense and in real time (using phase conjugation), has been considered in the context of microcircuit production,²⁻⁵ but the authors know of no recent work in which the mask is replaced by a hologram. Earlier work seems to have rejected holography possibly as a result of the limiting effects of speckle. Some of the imaging requirements in VLSI, especially with respect to intensity uniformity, are likely to be difficult to meet in a holographic system in which the coherence requirements lead to difficulties such as this speckle noise. However these problems are not necessarily insuperable and it was felt that the high potential of the holographic technique demanded further investigation.

II. Design Considerations

From the wide variety of possible holographic arrangements we have carefully selected two which meet our particular requirements and which in our view offered a high likelihood of success. These two schemes are shown in Fig. 1 and have been derived in the following way:

(a) Submicron resolution using a visible or ultraviolet source requires an optical system with high numerical aperture. Since the classical resolution limit for coherent illumination is given by $\delta = 0.8 \lambda / \text{N.A.}$, the required numerical aperture (N.A.) for $\delta \leq 1 \mu\text{m}$ and $\lambda = 250 \text{ nm}$ is $\text{N.A.} \geq 0.2$.

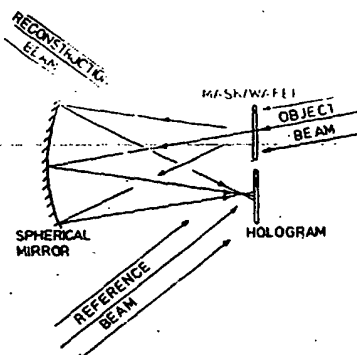
The authors are with SERC Rutherford Appleton Laboratory, Chilton, Didcot, Oxon OX11 0QX, U.K.

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a) MIRROR SCHEME



b) PROXIMITY SCHEME

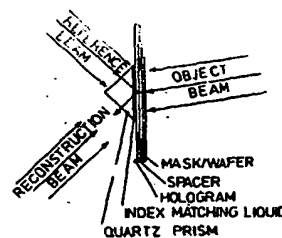


Fig. 1. Two holographic schemes for high-resolution lithography.

(b) Excimer lasers are most attractive sources for lithography because of their high mean power and their short wavelength which offers improved resolution and a good match to photoresists. However currently available models are not highly coherent sources and do not necessarily have output wavefronts free of optical distortion. To record holograms which can reconstruct an exact replica of the original object (mask in this case) it is important to find geometries which require minimum coherence and wavefront flatness of the source. In our schemes the transverse coherence and wavefront flatness requirements are minimized by recording the hologram in a plane very close to the mask or an image plane of the mask, and by a careful spatial match of the reference and object beams at the hologram. The temporal coherence (spectral bandwidth) requirement is minimized by use of a diffraction grating. Figure 2 illustrates these techniques in a simple arrangement.

An additional benefit of such schemes is their insensitivity to alignment accuracy, movement during recording or reconstruction, and laser wavelength stability.

It would appear from the above that the closer the hologram plane approaches the mask (or its image plane) the better. However there is an opposing requirement, that small defects or dust on the hologram should not mar the reconstructed image, and this sets a minimum acceptable distance between the hologram and the mask image plane. Typically a specification may require an insensitivity to dust or defects up to a size limit of say $10\text{ }\mu\text{m}$ in a system with $\text{N.A.} = 0.25$, which requires that the area of hologram contributing to each image point has a size $\gg 10\text{ }\mu\text{m}$ (say $50\text{ }\mu\text{m}$), and this would, in the proximity device, for example, result in a minimum spacing of $100\text{ }\mu\text{m}$.

(c) A crucial requirement is for an almost total lack of background noise in the holographic image since this gives rise to speckle and other spurious interference patterns. To achieve this there must be an almost total absence of scatter and stray reflections in the optical system both during recording and in reconstruction. Consequently diffusing components must

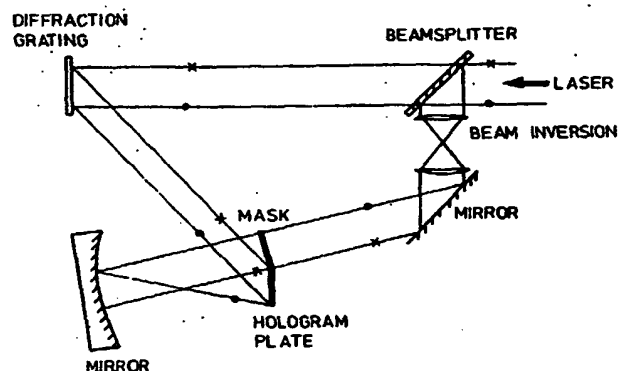


Fig. 2. Hologram recording arrangement designed to minimize the requirements on the transverse and temporal coherence and wavefront flatness of the laser source.

not be used and all surfaces, especially those close to the hologram and mask planes, must be very clean and have a minimum of surface defects. The holographic recording medium must also be scatter free. This has led to the choice of photoresist, which has low scatter and high resolution. We note that coherent scatter is a great deal more serious than incoherent scatter and it may be possible in a given optical system to reduce this problem by using a less coherent source.

(d) Arrangements have been selected that make use of the potential of holography for high performance using simple and inexpensive optics.

(e) It is noted that the two schemes tested are similar to optical schemes already marketed in VLSI imaging machines and hence can be compared with current machine performance more easily.

(f) Geometry considerations. The geometry has been designed such that as far as possible only the wanted first-order reconstruction from the hologram exists. The principal benefit of eliminating unwanted orders in reconstruction is that energy will not go into these orders and the hologram will be more efficient into the wanted $+1$ order. Figure 3 represents a holo-

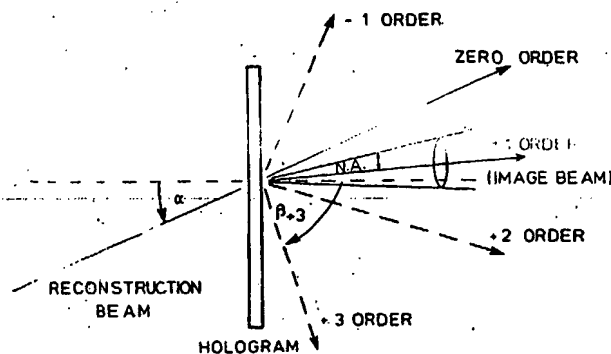


Fig. 3. Reconstruction geometry of holograms showing several possible reconstructed orders of the holographic grating.

gram reconstruction geometry where the directions of the various orders are given by

$$\sin \beta_{\pm n} = \pm \frac{n\lambda}{d} - \sin \alpha, \quad (1)$$

where n = order number,
 λ = wavelength, and
 d = hologram grating spacing.

For simple geometries as shown in Fig. 3 the requirement that orders do not exist in the image space is

$$\beta_{\pm n} \geq 90^\circ, \quad (2)$$

and if this is substituted into Eq. (1),

$$\pm \frac{n\lambda}{d} - \sin \alpha \geq 1 \quad (3)$$

or

$$\pm n (\sin \beta_{+1} + \sin \alpha) - \sin \alpha \geq 1,$$

where β_{+1} is the direction of the wanted reconstruction (+1 order).

If, for example, $\beta_{+1} = 0^\circ$ as in the mirror scheme, for the -1 order to be absent,

$$\alpha \geq -30^\circ. \quad (4)$$

For the $+2$ order to be absent, $\alpha \geq 90^\circ$. This is not possible but we can ensure that the $+2$ order does not overlap with the $+1$ order. From Fig. 3 it can be seen that this is so if

$$\beta_{+2} - \beta_{+1} \geq 2 \sin^{-1}(\text{N.A.}). \quad (5)$$

In our example, $\beta_{+1} = 0$, and from Eq. (1), $\beta_{+2} = \alpha$. Therefore

$$\alpha \geq 2 \sin^{-1}(\text{N.A.}), \quad (6)$$

which for $\text{N.A.} = 0.25$ gives $\alpha \geq 29^\circ$. A value of α of 50° was used in the mirror scheme.

(g) For accurate reconstruction fidelity the reconstructed image beam must be an exact phase conjugate of the original object beam, and this is only satisfied if the reconstructing beam is also an exact phase conjugate of the recording reference beam. Two possibilities exist to meet this requirement: the reference and reconstructing beams must both be plane waves, or

spherical waves of opposite curvature, or the reconstructing beam is generated from the reference beam via a phase conjugate mirror and in this case distortion on these wavefronts does not degrade the resulting image. We have chosen to use a plane wave reference beam coupled to a geometry which is insensitive to some wavefront distortion.

III. Mirror Holographic Scheme

A. Description

Figure 1 illustrates the arrangement used. The reference and reconstruction beams are only present for recording and reconstruction, respectively, and the mask is replaced by a photoresist coated plate to record the reconstruction.

A commercial line-narrowed KrF excimer laser (Lambda Physik EMG 150) capable of producing 800 mJ in a polarized beam of spectral bandwidth $\approx 0.2 \text{ cm}^{-1}$ and at a repetition rate of 10 Hz was the holographic source.

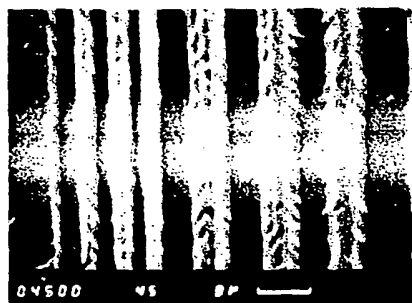
Shipley AZ2400 photoresist $1 \mu\text{m}$ thick on glass substrates was used for recording both the hologram and reconstructed image. This resist has an absorption depth of $\sim 0.3 \mu\text{m}$ at the KrF wavelength (249 nm)¹⁰ and resulted in a holographic recording exposure of $\sim 5 \text{ mJ/cm}^2$ and a reconstruction efficiency of 5–10%. These efficiencies were obtained by coating the hologram with 60 nm of aluminum and using the hologram in reflection for reconstruction. To ensure that the lithographic images so produced were etched through the complete thickness of the image photoresist, exposure levels of $\sim 200 \text{ mJ/cm}^2$ were required. Single shot recording and multishot reconstruction gave the best results.

A kinematic mount for both hologram and mask/resist image-recording plate was constructed to enable precise relocation of both hologram and image plate. Relocation in the correct plane to well within the depth of focus is required to maintain optimum resolution and fidelity of the recorded image. The mechanical arrangement satisfied this requirement thus ensuring optimum focus even when recording and reconstruction were separated in time by more than one day. There proved to be no need to have a focus adjustment on reconstruction.

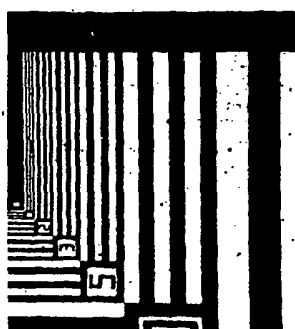
The $F/2$ mirror was approximately spherical (very low-cost spherical mirror) with low scatter and all optics were carefully cleaned to ensure minimum scatter. The glass substrate for the resist coated plates absorbed strongly at 249 nm and so eliminated reflections from its rear surface. The KrF laser beam could be expanded up to several centimeters in beam diameter to enable large area holograms to be recorded and thereby enable an investigation of image fidelity over large field sizes.

B. Experimental Results

Holographic images etched into resist using the technique described above were inspected using a high power optical microscope, gold coated and placed in a



(a)



(b)

Fig. 4. (a) Scanning electron micrographs of the narrowest lines and spaces present in the mask reconstruction. The exposure dose, of $\sim 180 \text{ mJ/cm}^2$, was delivered in sixty laser pulses. The images were recorded on a $1\text{-}\mu\text{m}$ thick layer of AZ2400 resist spun on a glass substrate. (b) An optical transmission micrograph of the corresponding area of the mask.

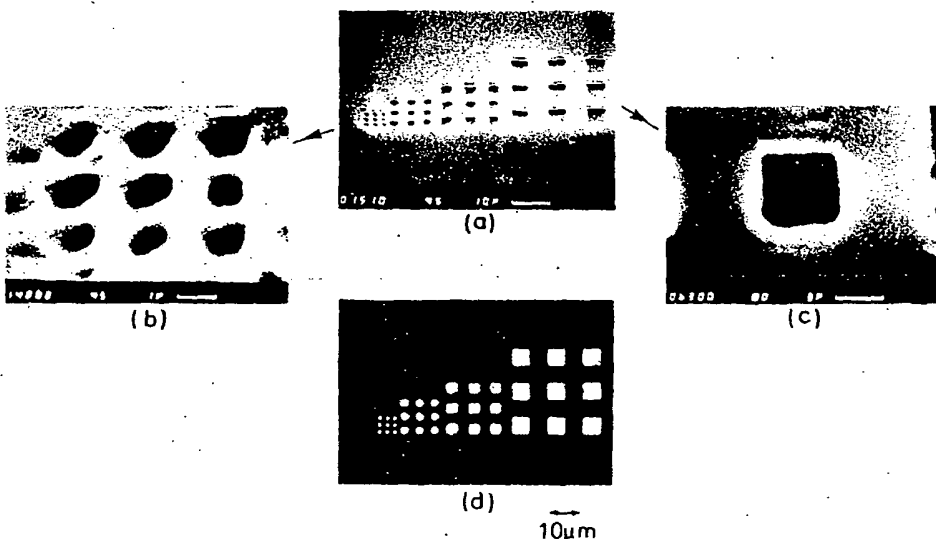


Fig. 5. (a), (b), and (c) Scanning electron micrographs of the smallest square features present in the mask reconstruction. The exposure dose of $\sim 180 \text{ mJ/cm}^2$ was delivered in sixty laser pulses. The images were recorded on a $1\text{-}\mu\text{m}$ thick layer of AZ2400 resist spun on a glass substrate. (d) An optical transmission micrograph of the corresponding area of the mask.

scanning electron microscope. Figures 4 and 5 show images obtained in this way. A resolution mask was used with various line and dot patterns. Figures 4 and 5 show the most difficult patterns to record well because of coherent interaction between the closely spaced lines or dots, and some residual interference effects can be seen. Also shown are optical microscope images of the relevant areas of the original mask.

The $1\text{-}\mu\text{m}$ lines and dots are clearly recorded. There is little evidence of speckle problems although there are regular edge ripples, particularly noticeable on the lines, which we believe to be due to a spurious coherent reflection rather than scattered light.

The spectral width of the reconstructing beam can normally be much greater than that required for recording. Figure 6 demonstrates that, although degraded, $2\text{-}\mu\text{m}$ features are still resolved when the reconstructing bandwidth was increased to the full bandwidth of $\approx 50 \text{ cm}^{-1}$ for the KrF laser.

To date, we have recorded holograms over an image field diameter of 40 mm and demonstrated that resolution is not affected over this area despite large differences in the amount of mirror aberration across it.

IV. Proximity Scheme

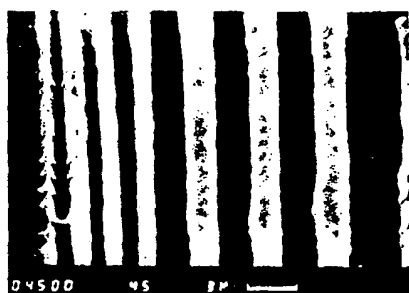
A. Description

This scheme, first used in a holographic arrangement by Stetson,¹¹ has obvious attractions in its simplicity, high numerical aperture, and insensitivity to mechanical instability and optical imperfection. Since all points on the hologram are optically equivalent to all other points, being the same distance from the object/image position on the mask, there is no difficulty in scaling up to large areas within the bounds set by exposure time and pulse energy.

One difficulty results from the presence of the reflected reference beam which gives rise to a three-beam interference pattern in the photoresist. This pattern is polarization sensitive due to the different phase



(a)



(b)

Fig. 6. (a) and (b) Scanning electron micrographs of the mask reconstruction when the reconstructing laser source bandwidth was increased to 50 cm^{-1} .

shifts on total internal reflection and due to the vector addition of noncollinear beams. The intensity distribution in the photoresist can be calculated by carrying out a vector addition of the field amplitudes of the three contributing beams, taking account of their relative phases. This distribution will depend on the angles of incidence of reference and object beams, on the absorption coefficient of the photoresist, on the input intensity ratio between the beams, and on the polarizations of the two beams. Figure 7 demonstrates the qualitative form of the intensity distribution which applies over a wide parameter range. It can be seen, in particular, that the fringe pattern becomes inverted as

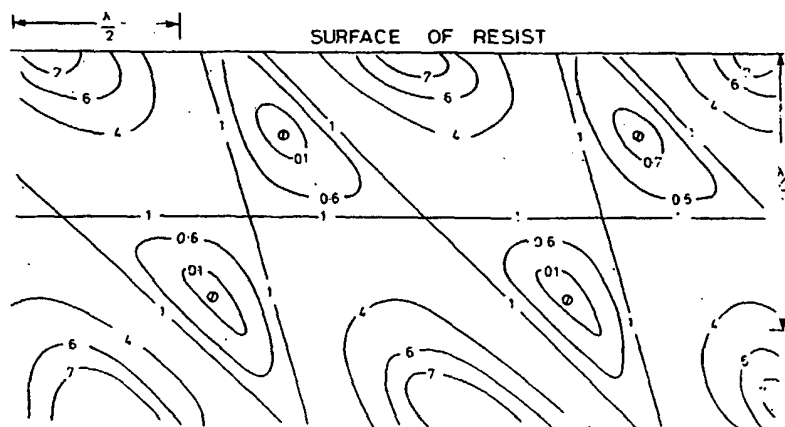


Fig. 7. Typical intensity distribution within the photoresist layer for the proximity holographic scheme. The contour values represent relative intensity. Reference beam with s polarization and incident at 57° to interface. Object beam s polarized and at 0° to interface. Absorption depth in resist $\gg \lambda$.

one proceeds through the resist, high intensity regions changing to low intensity and vice versa. The development process which etches preferentially the high intensity regions will either stop before it reaches the plane of uniform illumination or proceed through this plane and annihilate the contoured surface hologram already produced. The maximum depth of the surface contour hologram is thus limited (in our example the limit is approximately $\lambda/4$) so limiting the holographic efficiency which depends directly on this depth. The necessity to operate the hologram in transmission in this scheme also makes it difficult to achieve high holographic efficiency.

An argon-ion laser operating at 458 nm was used for initial tests of this scheme. Its wavelength was not a good match to the photoresist (AZ1350) and resulted in exposure levels being higher than was desirable.

Holograms were recorded with 100 mJ/cm^2 and reconstructed images in photoresist required exposures of $\sim 500 \text{ mJ/cm}^2$. Holographic efficiencies of $\sim 5\%$ were typical. They were limited by a need to keep down the exposure time to minimize the risk of movement during exposure and to minimize the risk, in our unoptimized arrangement, of a reduction in image fidelity due to nonlinearities of the hologram. It is expected that much higher efficiencies are achievable with good image fidelity if proper optimization is carried out.

B. Experimental Results

Holograms of a high-resolution mask were recorded and reconstructed into photoresist by lithography. The lithographic images were inspected optically and in a scanning electron microscope. Figure 8 gives examples of reconstructed images along with the original mask image for comparison. The $1\text{-}\mu\text{m}$ line was an excellent replica of the original with a departure from straightness amounting to no more than $\pm 0.15 \mu\text{m}$. This small imperfection of the image results from the presence of background speckle caused by residual scatter in the system optics. This we believe can be largely eliminated with improved polishing and handling of the optics.

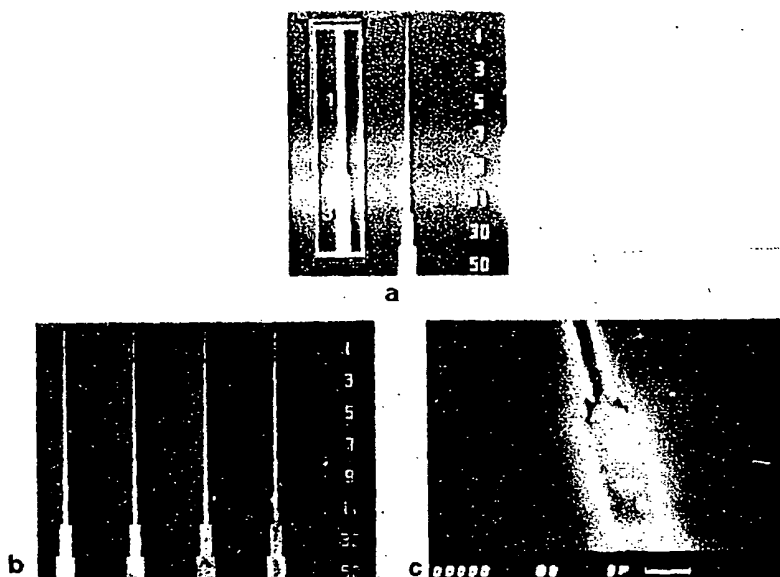


Fig. 8. (a) Optical transmission micrographs of the mask used for resolution tests in the proximity arrangement. Numbers refer to the width of the line in microns. (b) Optical transmission micrograph of the reconstructed image of the mask recorded in 0.3- μ m thick AZ1350 resist layer on glass. (c) Scanning electron micrograph of a small area of the reconstructed image showing detail of the 1- and 3- μ m lines.

V. Conclusions

We have demonstrated that micron and submicron features can be recorded holographically and can be etched into resist in reconstruction to a high level of fidelity with a speckle-free process.

We have demonstrated holography at 249 nm, perhaps for the first time, and measured reasonable efficiencies at modest exposure levels. A commercial excimer laser operating at 1 J/100 Hz might be expected to record a hologram for a complete 10-cm (4-in.) mask in a single shot and imprint the image on the entire wafer with an exposure time of <1 s.

Reconstruction efficiencies up to 10% have been measured with good image fidelity. Efficiencies up to 25% have been observed but with reduced image fidelity. The reason for this may be the onset of optical damage to the resist at higher exposure levels,¹² but we have no reason to doubt that higher efficiencies with good image quality will be achievable in the appropriate conditions.

We have shown that the technique scales up to field sizes of at least 40 mm in diameter without degradation and we expect to be able to scale up to larger field sizes without difficulty. It is notable that 1- μ m resolution over a 40-mm field size corresponds to a total information storage $\geq 10^9$ bits.

This paper has reported the first results of a pilot study to look again at one potential use of holography in microcircuit lithography. Concentrating only on resolution, freedom from speckle and scalability in area, the results have been encouraging in relation to effort expended. A more extensive analysis is now required to address these aspects in more detail and also to look at aspects not so far considered. These would include the problem of exact registration of images with good dimensional stability over large image distances, quantitative assessment of image fidelity

over large areas, and optimization of the process both to increase the reconstruction efficiency and to ensure adequate uniformity of illumination across the image.

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